NA61/SHINE Project

Extension for 2025-2029

JINR participation (Theme 1087: Research on Relativistic Heavy and Light Ion Physics. Experiments at the Accelerator Complex Nuclotron-M/NICA at JINR and CERN SPS)

Project leader: A. Malakhov
Deputies: A.Dmitriev, A.Zaitsev

JINR Management (1 person):
V.Matveev

VBLHEP (9 persons):
M.Buryakov, A.Dmitriev, V.Golovatyuk, V.Kireyeu, R.Kolesnikov, A.Malakhov, G.Melkumov, M.Rumyantsev, A.Zaitsev

DNLP (5 persons):
A.Krasnoperov, G.Lykasov, V.Lyubushkin, B.Popov, V.Tereshenko

Institute of Physics and Technology of MAS, Ulaanbaatar, Mongolia (6 persons):
B.Baatar, Ts.Baatar, N. Khishigbuyan, M. Sovd, B. Otgongerel, M. Urangua

Sofia University "St. Kliment Ohridski", Bulgaria (4 persons):
M.Bogomilov, D.Kolev, S.Ileeva, R.Tsenov

The American College, Madurai, India (2 persons):
N. Marimuthu, S. Sanila

Outline

Collaboration

Azerbaijan:	National Nuclear Research Center, Baku
Bulgaria:	Faculty of Physics, University of Sofia, Sofia
France:	LPNHE, University of Paris VI and VII, Paris
Germany:	Karlsruhe Institute of Technology, Karlsruhe
Hungary:	Wigner Research Centre for Physics of the Hungarian Academy of Sciences, Budapest
	Eötvös Loránd University, Budapest
Japan:	Institute for Particle and Nuclear Studies, Tsukuba
	Okayama University, Okayama
Norway:	University of Bergen, Bergen
	University of Oslo, Oslo
Poland:	Jan Kochanowski University in Kielce
	Institute of Nuclear Physics, Polish Academy of Sciences, Cracow
	National Centre for Nuclear Research, Warsaw
	Jagiellonian University, Cracow
	AGH – University of Science and Technology, Cracow
	University of Silesia, Katowice
	University of Warsaw, Warsaw
	University of Wrocław, Wrocław
	Warsaw University of Technology, Warsaw
Russia:	Institute for Nuclear Research, Moscow
	Joint Institute for Nuclear Research, Dubna
	National Research Nuclear University (Moscow Engineering Physics Institute), Moscow
	St. Petersburg State University, St. Petersburg
Serbia:	University of Belgrade, Belgrade
USA:	Fermilab, Batavia
	University of Notre Dame, Notre Dame
	University of Colorado, Boulder
	University of Hawaii at Manoa, Honolulu

148 participants,
29 institutions,
11 countries

p.24

"4. Study of the physics of strongly interacting matter, including the search for a critical point, the study of deconfinement, collective flows and the formation of an open charm in the NA61 experiment at SPS (CERN) — 2024–2030."

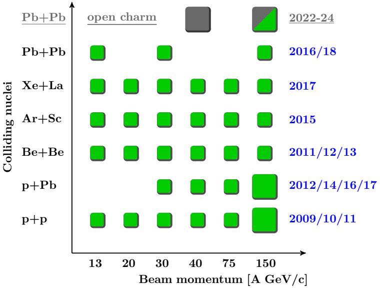
p.10

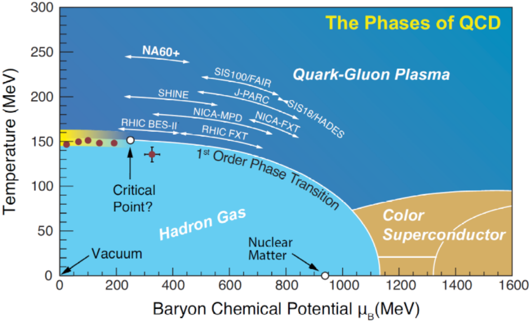
"JINR has been an important player with its participation in the heavy-ion programme at the CERN SPS first in WA98 and NA49/NA61, then in ALICE. These activities have been the motivation and source for the Mega-Science project NICA."

NA61/SHINE physics program

Strong interactions physics:

- study the properties of the **onsets of deconfinement and fireball**
- search for the **critical point** of strong interacting matter
- direct measurements of **open charm**





Neutrino and cosmic ray physics:

- ......

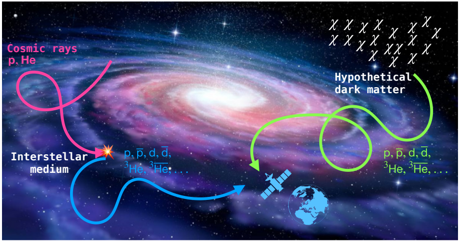
NA61/SHINE physics program

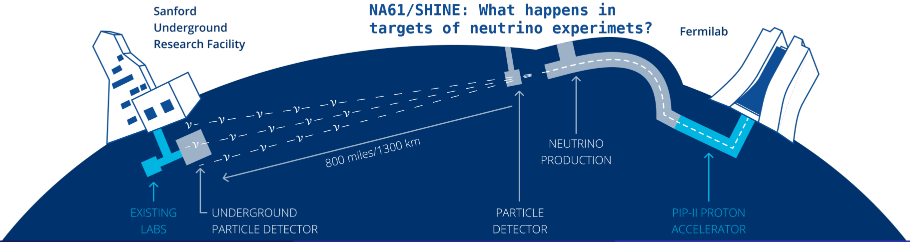
Strong interactions physics:

- ……

Neutrino and cosmic ray physics:

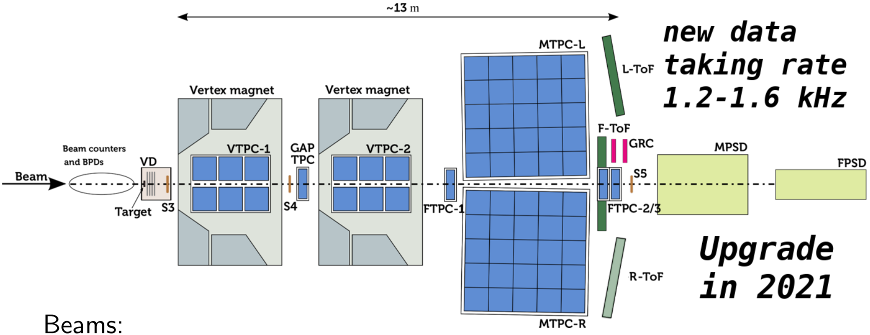
- **measurement for** the J-RAPC (**T2K**) and Fermilab (**NuMI and DUNE**) neutrino experiments
- **measurements** of nuclear fragmentation cross sections and hadron production **to improve air shower simulations** and **understand the cosmic ray propagation in Galaxy**





NA61/SHINE facility

Fixed target experiment located at the H2 beam line of CERN – North Area



new data taking rate 1.2-1.6 kHz

Upgrade in 2021

Beams:

- ions (Be, Ar, Xe, Pb) p_{beam}=13A-150A GeV/c
- hadrons (π, K, p) p_{beam}=13-400 GeV/c
- $\sqrt{S_{NN}}$=5.1-17.3(27.4) GeV

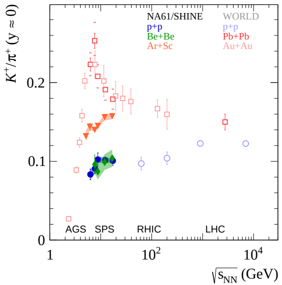
- new TPC readout electronics (contribution)
- new Vertex Detector (VD)
- new Time-of-Flight system (L-ToF)
- new Beam Position Detectors (BPDs)
- new Geometry Reference Chambers (GRC)
- upgrade of the Projectile Spectator Detector (PSD)
- new DAQ and trigger systems (contribution)

Strong internation program

Decisive contribution of the JINR group

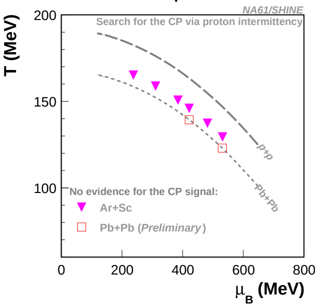
Key results 1

Onset of deconfinement



Unexpected collision energy dependence for small/medium size ions

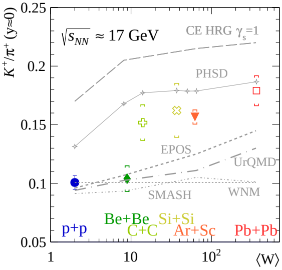
Critical point



No evidence

Values calculated from Becattini, Manninen, Gazdzicki, Phys. Rev. C73 2006

Onset of fireball



Unexpected system size dependence for small/medium size ions

p+p: Eur.Phys.J. C77 (2017) 10, 671

Be+Be: Eur.Phys.J. C81 (2021) 1, 73

Ar+Sc: OD,OF: Eur.Phys.J. C84 (2024) 3

CP: arxiv.org/pdf/2401.03445

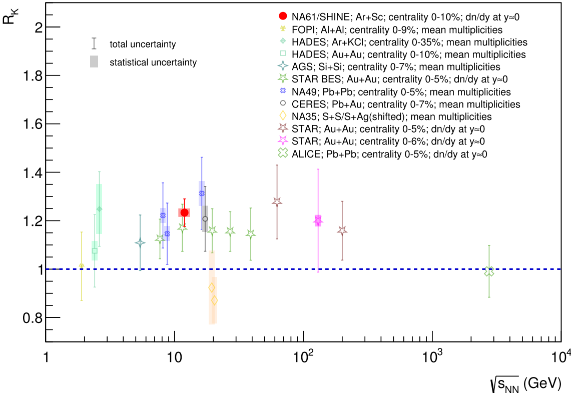
Pb+Pb: Phys. Rev. C66 (2002) 054902

Strong internation program

Decisive contribution of the JINR group

Key results 2

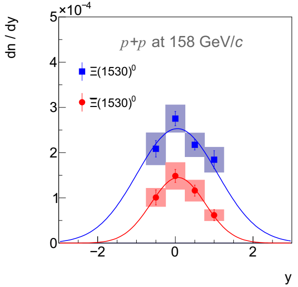
Anomaly excess of $K^{\pm}/K_s^0$ in Ar+Sc@75A GeV/c



$$R_K = \frac{K^+ + K^-}{2K_S^0}$$ *significantly higher than 1*

Ar+Sc: arXiv:2312.06572 [nucl-ex]
arXiv:2312.07176 [nucl-th]

$\Xi(1530)^0$ production in $p+p$@158 GeV/c



The only results in p+p at SPS energy

p+p: Eur.Phys.J.C 81 (2021) 10, 911

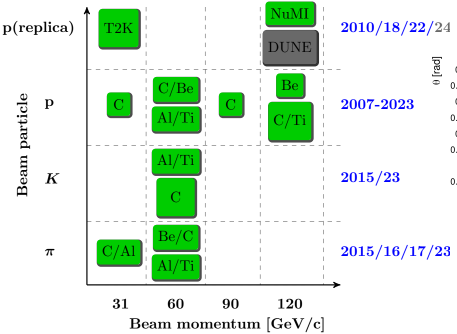
Neutrino program

Decisive contribution of the JINR group

Key results

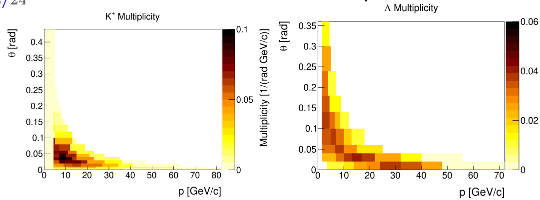
B.Popov is a convener of WG for JPAC

Collected systems:



Last results for FNAL:

$p + C$ at 120 GeV/c



Multiplicity measurements for $\pi^{\pm}, K^{\pm}, K^0_S, p, \bar{p}, \Lambda, \bar{\Lambda}$

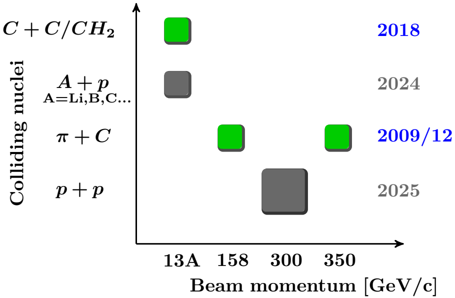
p+C: Phys.Rev.D 108 (2023) 072013
Phys.Rev.D 107 (2023) 072004

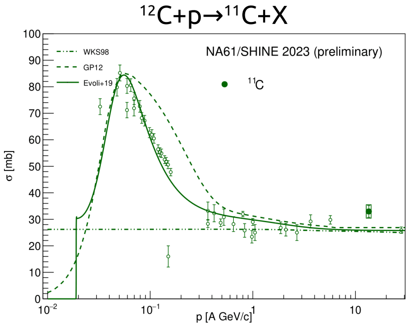
NA61/SHINE data decisively reduce the uncertenties of final results in neutrino experiments

Contribution of the JINR group

Key results

- Extensive air showers:
  - $p + C$ and $\pi + C$ interactions
  - synergy with neurtino program
- Propagation in Galaxy:
  - $d, \bar{d}$ and $\bar{p}$ production in $p + p$
  - nuclear fragmentation in $C + C/CH^2$



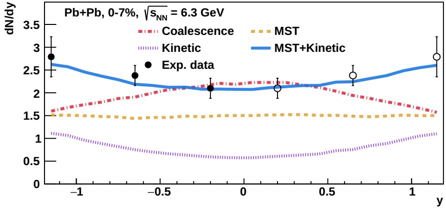


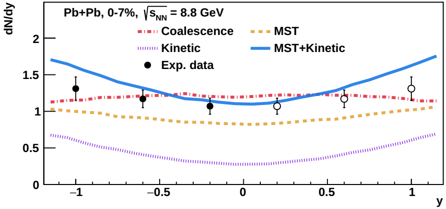
$\pi^- + C$: Phys.Rev.D 107 (2023) 062004

Unique results which cannot be described by the models needed to interpret high precision data on cosmic rays

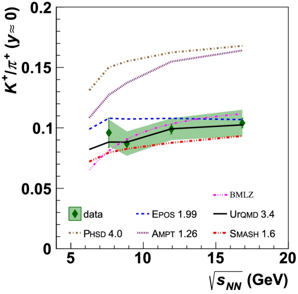
JINR contribution: Physics

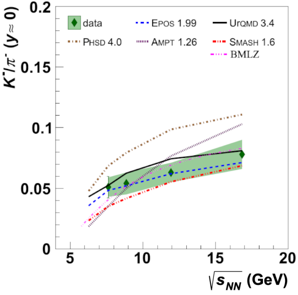
- Light cluster formation in midrapidity region in PbPb collisions





Pb+Pb: arXiv:2304.12019 [nucl-th]

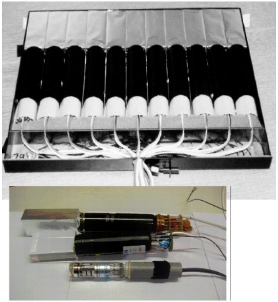


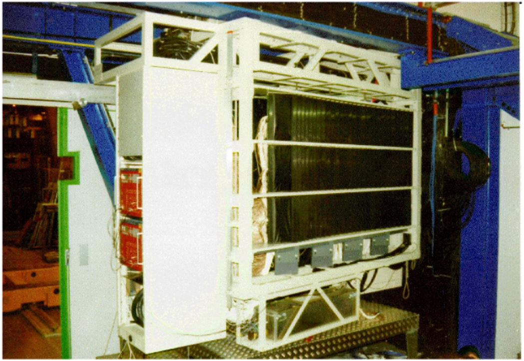


- Development of the self-similarity approach to describe hadron production in pp and AA collisions (BMLZ model)

p+p: Eur.Phys.J.A 57(2021) 3,91
Be+Be: Eur.Phys.J.A 58(2022) 6,112
Ar+Sc: arXiv:2402.03260 [hep-ph]
$\bar{B}/B$: J.Exp.Theor.Phys. 135(2022) 2,209

JINR contribution: ToF-LR detector 1995-2018





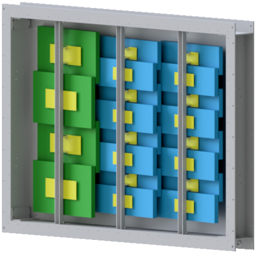
The previous NA49/61 ToF-LR:

- 891 scintillator counters per wall
- ToF-L (JINR contribution) put into operation in 1995-96
- time resolution: $\sim$ 75 ps
- significant degradation of all parts of ToF $\rightarrow$ the detector disassembling in 2018

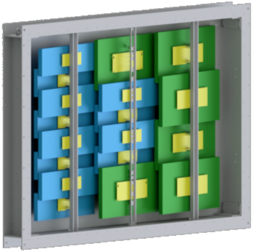
previous ToF-L: JINR Rapid Communications 5 (1997) p.69

JINR contribution: new ToF-LR detector 2021 - now

ToF-R
(possible commissioning in 2024+)



ToF-L
(commissioned in 2021)



beam

- MRPCs with gas module (16+4 detectors)
- modification of HV and gas systems
- LV system
- Front-end electronics (~2000 ch)
- ~~DRS4 readout~~
  picoTDC readout
- **Time resolution up to $\sigma_{\text{ToF}} \approx 36$ ps**

ToF-R: Nucl.Instrum.Meth.A under review

- MRPCs with gas module (12+6 detectors)
- Closed-loop gas system for two modules
- HV & LV systems
- Front-end electronics (1728 ch)
- DRS4 readout
- Time resolution: ~ 50 ps

ToF-L: Nucl.Instrum.Meth.A 1034 (2022) 166735
Phys. Part. Nuclei Lett. 21 (2024) 2, 121

JINR contribution: Other activities

- Strong interaction (charm) program:
  - 30M in target in 2022
  - 150M in target in 2023 **realistic goal is 440M in 2025**
- Neutrino program:
  - 160M with T2K replica target in 2022
  - 264M with thin targets for DUNE in 2023
- Cosmic ray program:
  - Close co-operation in preparation for high-statistics antimatter measurements in $p + p$ at 300 GeV/c
- Data reconstruction and software development for the runs since 2022:
  - Development and maintenance of the DRS4 calibration software
  - Geant4 model for new ToF detector
  - New algorithm for MRPC signal classification using ML

Software: JINST 19 P04002

- Upgrade of the trigger system

NA61/SHINE JINR group plans for 2025-2029

Hardware & data taking:

- ToF-L and overall facility maintenance during data taking
- ToF-R commisioning
- Participation in trigger R&D

Software:

- Service and further development of calibration software
- Reconstruction chain in the SHINE framework

Data analysis:

- the study of the light nucleus formation (d, t, $^3\mathrm{He}$, ..) in nucleus-nucleus interactions
- the study of hyperon and hypernuclei production in $Be + Be$, $Ar + Sc$, $Xe + La$, $Pb + Pb$ collisions
- analysis of anti-matter production in relativistic interactions
- the study of open charm production in heavy ion collisions
- measurement of hadron production for neutrino and cosmic ray physics
- further development of theory models for better understanding the collected data

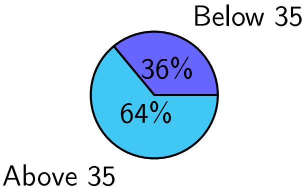
NA61/SHINE Management positions(4):

Dmitriev A. - Dep. tech. coordinator (1)
Malakhov A. - Collaboration board member (2)
Popov B. - Resource coordinator (3) and convener of neutrino analysis for JPAC (4)

№	Name	Lab	Category	FTE
1	Matveev V.	Directorate	scientific staff	0.1
2	Buryakov M.	VBLHEP	engineer	0.3
3	Kolesnikov R.	VBLHEP	engineer	0.7
4	Dmitriev A.	VBLHEP	scientific staff	0.8
5	Golovatyuk V.	VBLHEP	scientific staff	0.1
6	Kireyeu V.	VBLHEP	scientific staff	0.4
7	Malakhov A.	VBLHEP	scientific staff	0.4
8	Melkumov G.	VBLHEP	scientific staff	1.0
9	Rumyantsev M.	VBLHEP	scientific staff	0.3
10	Zaitsev A.	VBLHEP	scientific staff	0.6
11	Krasnoperov A.	DLNP	scientific staff	0.1
12	Lykasov G.	DLNP	scientific staff	0.3
13	Lyubushkin V.	DLNP	scientific staff	0.1
14	Popov B.	DLNP	scientific staff	0.9
15	Tereshenko V.	DLNP	scientific staff	0.1
	Σ FTE			**6.2**

* – PhD degree   * – doctorate degree

Age distribution:



Thesis's and publications in 2021-2024

- Two (2) PhD thesis were defended since 2021.
  Three (3) more are planned.

- 25 papers were published by JINR members for the last three years:
  - 11 of them are collaboration papers with JINR contribution
  - Five (5) are detector and methodological papers
  - Nine (9) are theory and analysis papers

Required resources

Item		Full cost (k$)	2025	2026	2027	2028	2029
1.	International cooperation	400	80	80	80	80	80
2.	Materials	500	100	100	100	100	100
3.	Equipment and third-party company services	50	10	10	10	10	10
Total budget:		**950**	**190**	**190**	**190**	**190**	**190**

Summary

- The unique results for heavy ion, neutrino and cosmic ray physics have been obtained. The future investigation is needed for:
  - search of the CP;
  - study of the QCD phase transition region;
  - new charm program;
  - further reduction of the flux uncertainties for neutrino oscillation measurements and etc.

- A huge amount of the joint work has been carried out for the NICA and NA61 projects[1]:
  - theoretical research – models, simulations;
  - detectors – MRPCs, electronics.

- The resources are rather modest, but justified by the physical tasks of the NA61/SHINE experiment.

[1] *prof. V.V.Burov (†): JINR participation in the experiment NA61 is very important since the research programme in this experiment lies in the main stream of the long-range programme in the field of relativistic nuclear physics at JINR.*

Thank you for your attention!

Backup slides

Beam time schedule in Run 3

Measurements	Field	2022	2023	2024	2025
Charm measurements in $Pb + Pb$	SI	30M events per two weeks	150M events per four weeks	three weeks of *Pb* beam at 150A GeV/c	four weeks of *Pb* beam at 150A GeV/c
T2K replica-target measurements	N	160M events per four weeks			
Thin-target C and Ti X-section	N, CR		264M events per six weeks		
Nuclear fragmentation cross-section	CR			week of a secondary light-ion beam at 13A GeV/c	
DUNE replica-target measurements	N			four weeks of proton beam at 120 GeV/c	
High-statistics measurements of p+p	SI, CR				four weeks of proton beam at 300 GeV/c

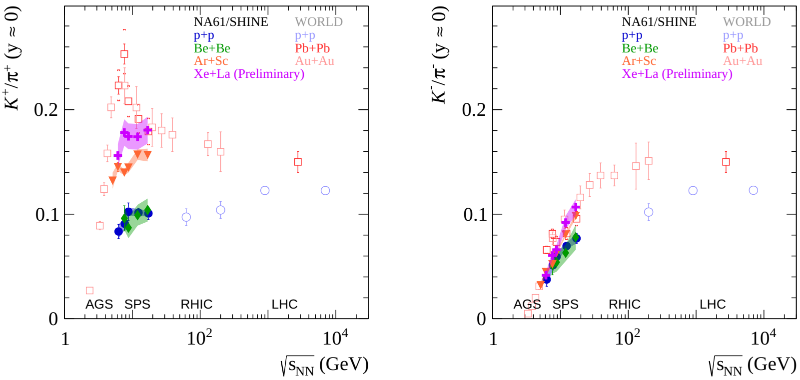
SWOT analysis

Strengths	Weaknesses
* Modern facility with unique parameters	* Delay with facility upgrade
* Relevance of the NA61/SHINE physics program to modern challenges of fundamental science	* Reduced amount of the beam time
* A large amount of experimental data collected for p+A and A+A interactions in a wide energy range from 13 to 158A GeV	* Time-consuming calibration procedure
Opportunities	**Threats**
* A new physics existence	* Facility accident
* The young people training for the NICA project	* Unsuccessful detectors delivery
* Development of new methods and technologies	* Changes in the world situation

Plots related to Onset of Deconfinement and Onset of Fireball

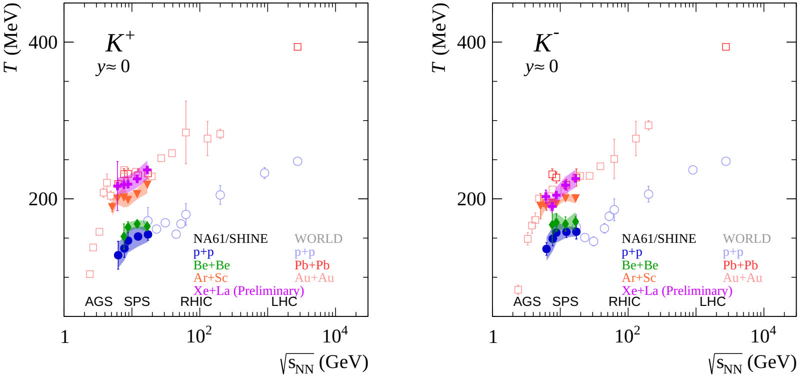
according to the request of the PAC for PP at the 55th meeting

K^+/π^+ and K^-/π^- at $y = 0$ (horn)

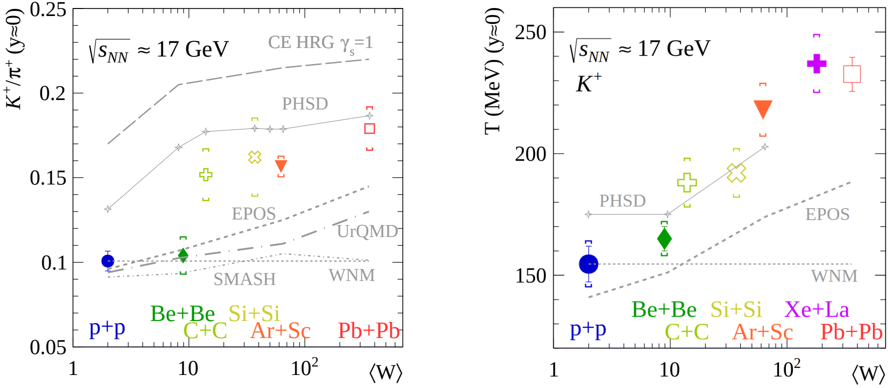


- Rapid change in the energy dependence of K^+/π^+ ratio in Pb+Pb collisions indicated the onset of deconfinement in the SPS energy range, as predicted within SMES
- Plateau-like structure visible in light systems (p+p and Be+Be)
- Ar+Sc systematically higher, Xe+La close to Pb+Pb at $\sqrt{S_{NN}} = 16.8$ GeV/c

Inverse slope parameter at midrapidity (step)

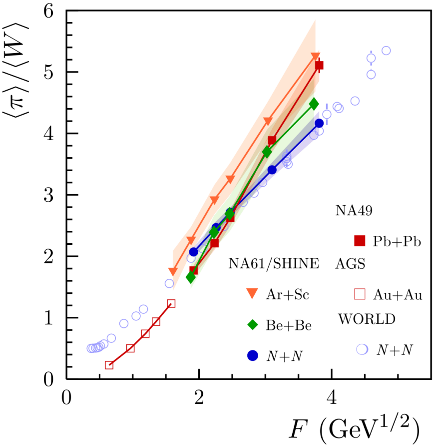


- Qualitatively similar energy dependence in pp, BeBe, ArSc, XeLa and PbPb
- Magnitude of T increases with the system size



- Rich collection of results on system size dependence of particle production in SPS energy range
- None of the models reproduce K^+/π^+ ratio or T in the whole $\langle W \rangle$ range

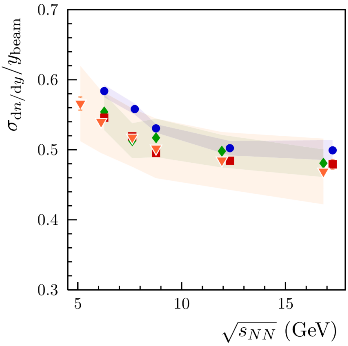
Pion multiplicity/number of wounded nucleons (kink)

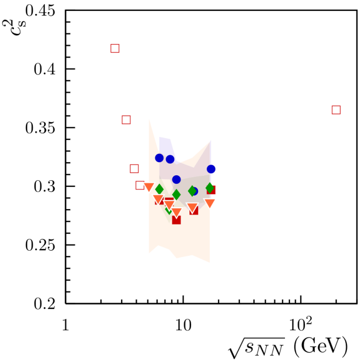


- Ar+Sc results systematically higher than the results for N + N, Be+Be and Pb+Pb at the lower energies
- Ar+Sc close to the Pb+Pb results at the highest energies
- Be+Be results close to Pb+Pb at lower energies and between N+N and Pb+Pb at higher energies

$$F = \left[\left(\sqrt{s_{NN}} - 2m_N\right)^3 / \sqrt{s_{NN}}\right]^{1/4}$$

Width of the y_π distribution - speed of sound (dale)





- The collision energy dependence of the pion rapidity distribution width is associated with the speed of sound c_S:

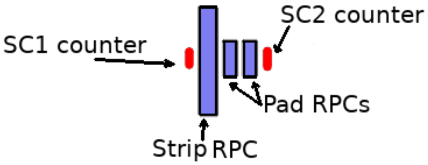
$$\sigma_y^2 = \frac{8}{3}\frac{c_S^2}{1 - c_S^4} ln(\frac{\sqrt{s_{NN}}}{2m_p})$$

- The results of NA61/SHINE from central Ar+Sc, Be+Be collisions, and inelastic N+N reactions need to be extended to lower energies for conclusion about a possible minimum

picoTDC test

Overview of the picoTDC test stand

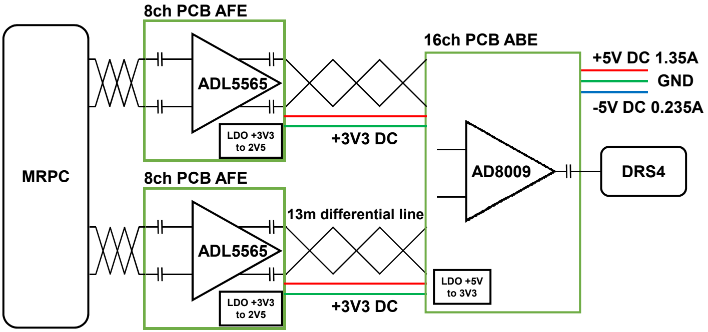
- HV - MPOD system
  ±6 kV (120 kV/cm) - PRPCs,
  ±5.75 kV (115 kV/cm) - MRPC
- $C_2H_2F_4$, i-C_4H_{10} and SF_6 (90/5/5)
  14 nl/h flow rate
- **A5203 FERS** readout(48ch):
  16+16ch for pad RPCs ($\sim$ 15x7.5 cm^2)
  16ch (8 strips) for MRPC ($\sim$ 15x10 cm^2)
- LV - lab.sources
  4.4 V/3.41A - analogue FEE (48ch)
  12 V/0.57A - picoTDC
- Front-end electronics:
  Analogue FEE with comparator
  NINO 160 mV threshold
- Two trigger sci-counters:
  Forward PMT SC1 ($\sim$ 12.5x10 cm^2)
  Backward SiPM SC2 ($\sim$ 9.5x9.5 cm^2)



Pb+Pb collisions at 150A GeV/c were registered!!!

Analogue front-end electronics - AFEC

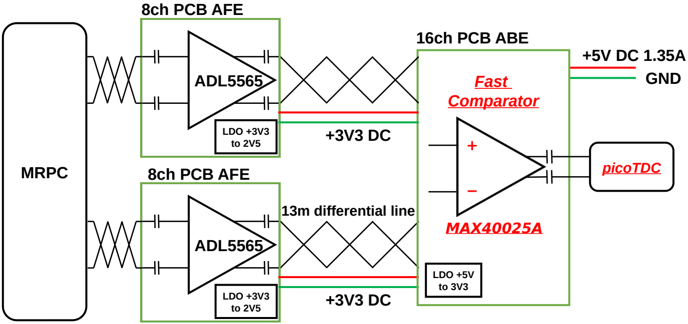
- The key idea is to modify front-end electronics for DRS4 readout, namely to replace the (Analogue Back-End) ABE part with fast comparator.



Front-end amplifier for DRS4

Analogue front-end electronics - AFEC

- The key idea is to modify front-end electronics for DRS4 readout, namely to replace the (Analogue Back-End) ABE part with fast comparator.



Front-end with fast comparator for picoTDC

picoTDC test during Pb run

Front view

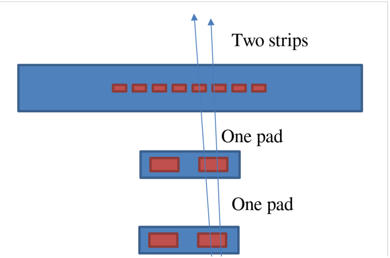
picoTDC test during Pb run

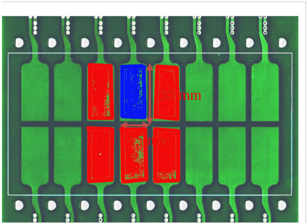
Back view

Event selection

1. Time cut on pad detectors (time < 78 ns);
2. **Low amplitude cut on pad detectors !!! Affect on PRPCs time resolution and efficiency**
3. No hits on nearest pads (distance to nearest hit > 3.9 mm – circle selection);
4. Fixed pads and strips
   (strip – #5 for analogue or #6 for NINO, both pads – #3);

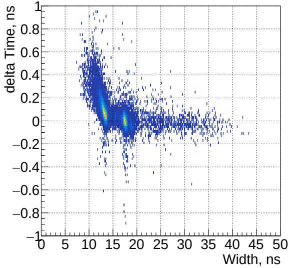
Efficiency calculation. Fixed strip ± 1
Time calculation. TA-correction + three equation system

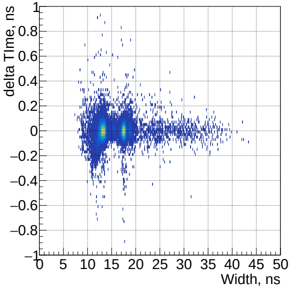




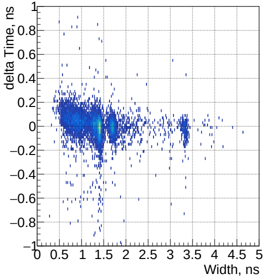
Results. TOT-correction with picoTDC

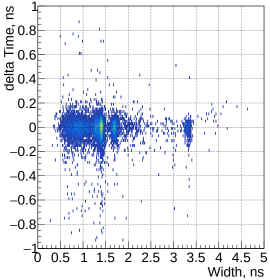
NINO



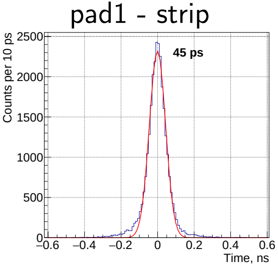


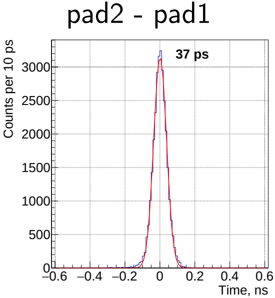
Analogue FFE

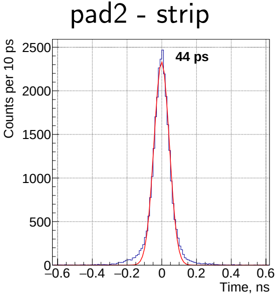




Results. NINO + picoTDC

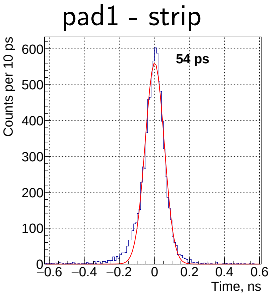


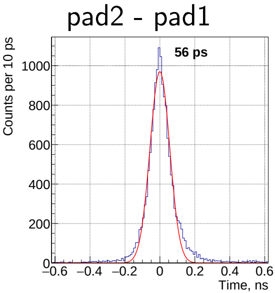


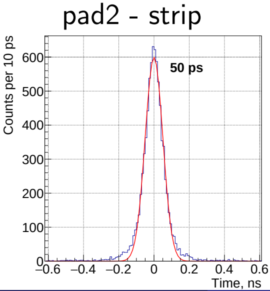


$$\sigma_{strip} \approx 36.1 \pm 0.66 \text{ ps}$$

$$\text{eff} = 97\%$$







$$\sigma_{strip} \approx 51.77 \pm 2.91 \text{ ps}$$
$$\text{eff} = 70\%$$

Thank you for your attention!